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Operations Research and Economics Division

ANALYSIS AND APPLICATION OF SHIELDING AND PROTECTION FACTOR RESEARCH

FINAL REPORT R-OU-155

Prepared for

Office of Civil Defense
United States Department of the Army

under

Office of Civil Defense Contract No. OCD-PS-64-56
Work Unit 1115C

RESEARCH TRIANGLE INSTITUTE · DURHAM, NORTH CAROLINA

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RESEARCH TRIANGLE INSTITUTE
Durham, North Carolina
FINAL REPORT
R-OU-155

Analysis and Application of Shielding and Protection Factor Research

by

E. L. Hill, D. R. Whitaker, and Wesley O. Doggett*

28 October 1965

Prepared for

Office of Civil Defense
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ABSTRACT

A review of gamma-ray shielding information was made to determine if existing methods for computing protection factors of structures agree with experimental data and to determine areas where shielding information is incomplete. Research subject areas analyzed include: modeling techniques, basement dose rates, simulated fallout, interior partitions, ceiling shine, ground roughness, azimuthal sectors, limited strips of contamination, and non-uniform source distributions. These analyses are used to determine the status of the present protection factor computational procedures. Major findings in each subject area are included and recommendations for additional experiments and for modifications to existing computational procedures are made. Some major findings are: (1) roof contributions as predicted by Spencer's Monograph agree within 1 to 15 percent with full-scale experimental measurements; (2) theoretical predictions of Spencer's Monograph for basement protection factors are usually non-conservative; (3) modeling is, in general, a useful, convenient, and accurate method of obtaining fallout protection offered by first stories and upper stories of full-scale structures; (4) floor-edge scattering into a basement can be a substantial source of radiation; (5) compartmentation makes model results increasingly non-conservative; (6) the pumped source method is conservative (15 to 40 percent) when compared with the limited data on actual fallout; and (7) the Engineering Manual is the most accurate of the commonly used protection factor computational procedures.

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 1

Summary

I. SCOPE AND OBJECTIVES

This constitutes the final report of the research completed under Office of Civil Defense Subtask 1115C, Analysis and Application of Shielding and PF Research, Contract No. OCD-PS-64-56. The objectives of this research were to: (1) determine if existing methods for computing protection factors agree with experimental data; and (2) recommend new investigations in areas where gaps exist in current shielding knowledge. This research supplements the findings of OCD Subtask 1115A (Reference 1). The contractual scope of work is enclosed as Appendix A.

The research subject areas which were analyzed included: modeling techniques, basement dose rates, simulated fallout, interior partitions, ceiling shine, ground roughness, azimuthal sectors, limited strips of contamination, and non-uniform source distributions. These analyses were used to determine the status of the present protection factor (PF) computational procedures including: Spencer's Monograph (Reference 2), AE Guide (Reference 3), Engineering Manual (Reference 4), Shelter Design and Analysis, Volumes 1 and 2 (References 5 and 6), NFSS Computer Program (Reference 7), Canadian and British AE Guides (References 8 and 9), Point Kernel Method (Reference 10), PM-100-1 Supplement 1 (Reference 11), the Praeger-Kavanagh-Waterbury Computer Program (Reference 12), and the RTI CDC-3600 Computer Program (Reference 13).

II. APPROACH

The work for this project was divided into two categories: (1) evaluation of full-scale and model experimental data, and (2) status of theoretical predictions of experimental results. These analyses are included as Chapters 2 and 3, respectively.

A review of gamma-ray shielding literature was made, personal visits were made to organizations involved in shielding research of the type required for protection factor analyses, and discussions were held with the experimenters at these organizations. Also, well-known experts were consulted for comments and opinions on applicable research. The organizations visited included the following: Nuclear Defense Laboratory (NDL); Protective Structures Development Center (PSDC); National Bureau of Standards (NBS); Technical Operations Research (Tech Ops); Edgerton, Germeshausen, and Grier, Inc. (EG&G); the U. S. Naval Radiological Defense Laboratory (NRDL); and the U. S. Naval Civil Engineering Laboratory (NCEL).

III. FINDINGS

A. Introduction

The National Fallout Shelter Survey has shown that there is a shortage of adequate fallout shelters. If protection factor calculations are in error, adequate shelters may be rejected in the NFSS. Therefore, it is important to have the best possible estimate of the protection factors (PF). Many experimental and theoretical investigations of structure shielding against fallout have been performed. Methods for theoretical prediction of experimental results are continually being revised to update them and bring them more in line with experiments. The major findings of the research review and the status of the computational procedures are presented in the following paragraphs by subject area.

B. Full-Scale Experiments

Several laboratories have performed full-scale experiments with calibrated sources and measured radiation intensities at different locations within structures. These experimental results were compared with Engineering Manual computations for certain cases. The major findings of the review of these experiments are:

1. In general, Engineering Manual theoretical reduction factors were within a factor of two of EG&G full-scale experiments on various structures (see Reference 1 for details). For a wood rambler house, the computed protection factor at the center of a bathroom shelter agreed within 4 percent with EG&G experimental values.

2. Early computational methods, such as Reference 9, predicted protection factors which were lower (conservative) by a factor of 1.5 or more when compared with Tech Ops experiments on various full-scale structures. Included were an Army barracks type of structure, an underground shelter, and residential type structures. For an open hole and residential basements, the theoretical predictions were conservative by a factor of 2 to 3.

3. Roof contributions measured by NDL for a full-scale concrete blockhouse agreed within 1 to 15 percent with Spencer's Monograph (Reference 2). Backscattered radiation was believed to have caused a discrepancy between experimental and theoretical ground contributions which varied with detector height. Experimental values were lower at 6 feet above the floor and

higher both at floor level and 1 foot below the floor.

4. NDL experimental and theoretical reduction factors (Spencer's Monograph) for ground contribution in a full-scale concrete blockhouse with wall weights of 48 to 139 psf agreed within 15 to 20 percent; the exponential attenuation of dose rate as a function of wall thickness was confirmed for detector heights of 0, 3, and 6 feet.

5. In unexposed and exposed basement experiments, with and without a first floor slab, NDL found that theoretical predictions based on Spencer's Monograph were usually non-conservative by as much as 30 percent.

6. For ground contribution through a single wall of a sand-wood blockhouse, DRCL found a dose rate midway between the center and sidewall to be 10 to 30 percent greater than at the center. Scattering was believed to be the source of this discrepancy, but effects of point sources rather than plane sources make this explanation questionable.

C. Model Experiments

The modeling approach to measurements of radiation attenuation in structures has been used by various laboratories. The major findings of the analysis of model experiments are:

1. In general, modeling is a useful and convenient method of estimating data on fallout protection afforded by full-scale buildings for first story and upper story locations. For both exposed and unexposed basements, uncertainties still exist which must be resolved before results can be considered completely valid. However, it is felt that the trends displayed by basement model data will be present in full-scale structures.

2. Experimental values of wall-scattered radiation, $G_s(\omega)$, were found to agree within 20 percent of Engineering Manual predictions by Tech Ops using a 1:12 scale steel model.

3. The basement dose rate increases by a factor of 2 for an infinite plane of contamination as the first floor slab becomes fully exposed, whereas the increase is by a factor of 4 for a 12-inch-wide plane (12-feet full-scale) adjacent to the Tech Ops 1:12 scale steel model building.

4. A correction factor to account for variation of basement dose rate with depth was derived from the Tech Ops model data in the course of the present research. The correction factor increases smoothly with depth.

5. The ratio of dose rate at the corner of a 1:12 scale steel model basement 3 inches below the first floor to that at the center is essentially unity for an infinite smooth field and increases to 1.3 for a limited field 24 inches wide (24-feet full-scale). This result seriously disagrees with the Engineering Manual (Reference 4), which will always predict a decrease in this ratio for ground contamination.

6. Monte Carlo and Moments Method shielding calculations were found to agree with Tech Ops experimental 1:12 scale steel model data, which show that two slabs are generally more effective than a single slab of equal mass thickness. The Engineering Manual procedure of using the product of barrier factors for the two-slab case is nonconservative by up to 30 percent when compared with experimental values.

7. Single slab buildup factors for plane-parallel radiation were found by NRDL to be always higher than for buildup factors in steel model compartmented structures. The largest discrepancy was 30 percent.

8. Failure to scale the density of ground and the density of air were estimated experimentally by DRCL to affect a 1:10 scale steel model shielding study by less than 10 percent for ground contribution.

9. Tech Ops, NRDL, and DRCL found that increasing the number of interior partitions makes model results increasingly nonconservative in predicting full-scale dose rates from ground contribution (i.e., dose rates predicted by the model are less than actual dose rates).

10. DRCL experiments indicated that an accuracy of ± 10 percent should be possible in scaling concrete walls with iron.

11. The Engineering Manual predictions agreed within 10 percent with Tech Ops 1:12 scale steel model data for a centrally located detector at the 3 foot first-story level, exposed to an infinite field of contamination. This supports the claim that the scaling procedure for simple structures with above-ground detectors is reasonably accurate.

12. Agreement between Tech Ops 1:12 scale steel model finite field data and the National Fallout Shelter Survey Computer Program (Reference 7) was not good (3 to 100 percent) for narrow planes, and was within 30 percent for wide planes (ratio of plane width to detector height greater than 10).

13. In the course of the research, it was noted that the dose rate per unit area of source distributed uniformly along a line parallel to the building walls varies inversely as the square of the geometric mean of the source-wall distance and the average source-detector distance. This enables determination of contribution from an outer plane of contamination by means of a simple equation if contribution from the inner plane is known.

14. The ratio of the dose rate of an upper story corner position to that at the center depends significantly both on the width of the plane of contamination and on the floor mass thickness. For width-of-plane to height-of-detector ratios less than or equal to 10, the ratio was found by Tech Ops in 1:12 scale steel models to be 1.4 for 20 psf full-scale floors and 2.5 for 80 psf full-scale floors. The corresponding factor for an infinite field and 50 psf full-scale floors was found to be 1.04.

15. Because of an interest in determining weathering effects on fallout, minimum theoretical computations were made using Tech Ops' model data. It was found, for example, that if a building (36 ft. wide x 48 ft. long) were surrounded solely by a limited plane of width W_c = 24 feet, the relative increase in dose rate at a first story detector location would be 38 percent if all of the radioactivity on the roof fell on the ground next to the wall. If, however, the building had been surrounded by an infinite plane of contamination, the increase would have been only 8 percent. Therefore, redistribution of fallout does not cause a significant change in PF if there is an infinite plane of contamination.

D. Simulated Fallout

Because of impracticality of using real fallout, the pumped source method of simulating fallout has been developed. The major findings of the review of the pumped source method of fallout simulation are:

1. The pumped source method is conservative when compared with real fallout on the ground and roof of a Butler Building and above an underground shelter. In EG&G tests comparing real fallout and a pumped source, the two methods disagreed by 15 to 40 percent.

2. Pumped source experiments simulating an infinite field showed ground contribution in the basement of a Butler Building without a first floor slab to be as much as 20 percent less than Engineering Manual calculations in

EG&G tests at the 1-foot level; they were as much as a factor of 2 less for a 6-foot level detector.

3. NRDL found that the Co^{60} pumped source method is satisfactory for simulating real fallout radiation in highly compartmented structures such as ships.

E. Ground Roughness

Ground roughness effects on protection factors are not accounted for in present computational procedures. However, it has been found by NRDL, EG&G, and DRCL that ground roughness can be an important parameter in analyzing protection factors of buildings. Major findings of the review of ground roughness experiments are:

1. The method of correcting for ground roughness in theory to agree with experimental results as if radioactive fallout were buried beneath a layer of earth (or an equivalent layer of air) appears adequate.

2. Both dose angular distribution experimental measurements and dose-height experimental measurements give consistent results for obtaining a theoretical ground roughness correction factor.

3. It is incorrect to use the pumped source simulation method in ground roughness experiments, because the continuous tubing eliminates much of the roughness effect.

F. Computational Procedures

Major findings of the analysis of protection factor computational procedures are:

1. Shortcomings occur in the Engineering Manual treatment of azimuthal sectors, first floor slab exposure, basement dose rates, interior partitions, ceiling shine, and ground roughness.

2. The Equivalent Building Method (Reference 6) offers advantages of speed and simplicity when comparison of alternative structure designs is involved. Results are within $\pm$ 10 percent of RTI and OCD calculations using the Engineering Manual. For simple buildings (one or two stories, sill heights above detector level, no partitions, infinite planes of contamination) in the range of 1,000 to 100,000 square feet.

3. The Protection Factor Estimator (Reference 14) is a simplified version of the Equivalent Building Method and agrees within $\pm$ 10 percent of the EBM for structures between 1,000 and 10,000 square feet in area. Outside of

these limits, the variation may be as much as 35 percent.

4. The various AE Guides (References 3, 8, and 9) and the NFSS Computer Program (Reference 7) are within $\pm$ 20 percent of Engineering Manual results for simple buildings such as blockhouses, but should not be used for complicated structures.

IV. RECOMMENDATIONS

The recommendations resulting from the research reported herein are:

1. Wall-scattered radiation, $G_s(\omega)$, is one of the most uncertain parameters in the Engineering Manual procedure. Because of the difficulty of isolating effects experimentally and the lack of theoretical work on this parameter, it is recommended that Monte Carlo calculations be performed to better understand the angular distributions of wall-scattered radiation.

2. The only known studies on sand bag shielding left cracks between the bags which permitted radiation streaming. A more efficient method of stacking the bags possibly could be found. Further experiments and analyses on sand bag shielding are recommended.

3. Additional model experiments of the type reported by DRCL for side wall scattering should be performed with plane sources instead of point sources to determine the resulting dose rates near the sidewalls.

4. Tech Ops' procedures on scaling buildings to determine ground contribution in exposed and unexposed basements do not adequately predict full-scale measurements. Therefore, it is recommended that suitable full-scale exposed and unexposed basement experiments be made to allow an evaluation of the scaling method for model data and to:

    a. Determine the radiation originating from grade level which is scattered into a basement of a partially exposed first floor slab.

    b. Determine the effect of ground roughness on detectors in a basement and in a first story with the first floor slab partially and fully exposed.

    c. Make off-center basement measurements to compare with center measurements. The Engineering Manual predicts a ratio of unity for basement corner to center dose rates, whereas the model experimental ratio is 1.3 for a 24-inch-wide (24-feet full-scale) plane of ground contamination.

5. If the importance of floor-edge scattering observed in models is verified by the recommended full-scale experiment, it is recommended that a calculation procedure be developed for analyzing basements

and first stories in buildings with fractional first floor slab exposure.

6. It is recommended that Engineering Manual calculations be performed for basement off-center detectors subject to limited planes of contamination to allow comparisons of dose rate data with Tech Ops model results.

7. Reference 1 shows how the direct component of ground radiation penetrating a floor slab can actually give rise to an initial increase in dose rate, then a decrease, as the detector is moved downward from the slab. This should be accounted for in the next revision of the Engineering Manual.

8. For structures with numerous interior partitions, it is recommended that the barrier factor be determined by

$$B_w = B_w(X_e)\ B_w(X_p + kX_i)$$

where B_w = barrier factor for the exterior wall, X_e = psf of exterior wall, X_p = psf of parallel partitions, X_i = psf of cross partitions, and $k = \frac{1}{2}$. If a single barrier of the total mass thickness is used in an analysis for compartmented structures, it should be regarded as a conservative method of calculation.

9. It is recommended that the ceiling shine procedure proposed by Tech Ops be included in the revision of the Engineering Manual as an ancillary method for handling upper stories of tall buildings.

10. Since all of the more accurate methods for computing PF's (including the various computer programs) use the azimuthal sector method, it is recommended that a more accurate procedure be incorporated into the present Engineering Manual procedure to account for the variation in contribution of azimuthal sectors of identical size centered on different azimuthal angles. Subsequent incorporation into computer programs is advisable.

11. For rough terrain, such as plowed fields, macroscopic ground roughness would affect real fallout fields to a greater degree than it would the pumped source. Although results in the experiments comparing the pumped source method with real fallout were quite similar, ground roughness was not severe. Therefore, effects of macroscopic ground roughness should be measured experimentally, and calculated using Monte Carlo procedures.

12. Until recommendation 10 or its equivalent is implemented, a factor of 2 should be used in calculational procedures to decrease the dose rate above moderately rough terrain (plowed ground) to account for ground roughness.

13. Additional ground roughness experiments should be performed on surfaces most frequently occurring around fallout shelters. It is recommended that laboratory model tests be performed on geometrically simple ground roughness patterns like parallel furrows or circular patterns using scaled contamination and roughness. If these results indicate significant reductions in dose rates due to ground roughness, full-scale measurements should be made to determine ground roughness factors for surfaces expected around fallout shelters. Examples of such surfaces are grass, sidewalks, tar and gravel roofs, and city streets.

14. Better instrumentation should be used on all future ground roughness tests, since one of the major problems in past experiments was caused by instrument errors and the influence of heat, dust, and low radiation intensity on instrument stability.

Chapter 2

Methods of Experimental Confirmation

I. INTRODUCTION

Although attenuation of gamma rays is quite well described by various theories, all of the problems for which solutions can be readily obtained require rather simple geometries and often necessitate approximations when applied to real structures. The OCD publications Design and Review of Structures for Protection from Fallout Gamma Radiation (Engineering Manual) (Reference 4), Shelter Design and Analysis, Volumes 1 and 2 (References 5 and 6), and the Protection Factor Estimator (Reference 14), which are outgrowths of Dr. L. V. Spencer's NBS Monograph 42 (Reference 2), are attempts to systematize the analysis of building protection factors (PF). In order to determine the accuracy of PF computational procedures, various laboratories have performed shielding experiments to determine the protection factors of various structures.

The best method of determining the protection factor of a building is to measure radiation intensity or dose within the building exposed to fallout radiation. In the past, however, this proved to be quite difficult and expensive because of the radiation hazard involved, the large area required, exclusion of non-authorized personnel, and uncertainties in distribution or location of fallout. Thus, various alternative methods for determining protection factor have been devised.

This chapter discusses full-scale shielding experiments and modeling experiments. The use of simulated fallout methods such as the "pumped source" technique of pushing a radioactive source through thin tubing with water pressure in both type of experiments is emphasized.

II. FULL-SCALE SHIELDING EXPERIMENTS

A. Introduction

The accuracy of the Engineering Manual method of computing PF's can be measured by comparing results of an experiment with a detailed Engineering Manual computation. The following laboratories have performed full-scale experiments to measure radiation intensities at different locations within structures: Edgerton, Germeshausen, and Grier, Inc. (EG&G), Technical

Operations Research (Tech Ops), Nuclear Defense Laboratory (NDL), and the Defence Research Chemical Laboratories (DRCL) of Ottawa, Canada. The work of each of these laboratories and a comparison with the Engineering Manual for applicable cases are discussed below.

B. Edgerton, Germeshausen, and Grier, Inc., Experiments

Protection factor measurements were made for the following structures by EG&G: (1) Brookhaven National Laboratory Medical Research Center (Reference 15), (2) a single story stucco frame house (Reference 16), (3) an earth covered shelter (Reference 17), (4) selected structures in the Los Angeles area (Reference 18), (5) two 2-story and three 1-story typical residential structures (Reference 19), and (6) an underground shelter and an above grade shelter (Butler Building) with a basement (Reference 20).

RTI (Reference 1) evaluated the research covered in References 15 through 18. Included in this research are detailed Engineering Manual computations for the Brookhaven National Laboratory Medical Research Building, the Laboratory of Nuclear Medicine and Radiation Biology at UCLA, the Communications Center of the Los Angeles Police Department, and a classroom at North Hollywood High School. A comparison of these results with the experimental radiation dose contributions determined by EG&G indicated the accuracy of the Engineering Manual. The results showed that, in general, the theoretical contributions were within a factor of two of the experimental values and always indicated conservative protection. That is, the theoretical protection factor was always less that the measured quantity. It is believed that the deviation between results was primarily due to interior contents, pipes, cross beams, etc., which are ignored in the theoretical calculations or whose mass could not be accurately estimated.

In an unpublished report (Reference 19), EG&G has documented the measurement of protection factors in residential structures containing fallout shelters. The measurements were made with a fallout field simulated by the "pumped source" technique. These structures had previously been used in weapons effects tests, after which they were modified to improve the protection of the shelters. (Modifications consisted of adding concrete walls in front of doors, concrete slabs over shelter areas, etc.). Calculations of protection factors were not reported by EG&G. Also, because detailed architectural and engineering data were not available, reliable protection factor calculations could not be made for the more

complex situations. However, based on minimum information and educated guesses, an Engineering Manual type calculation was made for the protection factor at the center of a bathroom shelter in a wood rambler house after the first modification (See Figure 1.9, Reference 19). The computed protection factor of 55 compared favorably with the measured value of 57. These results are believed to be satisfactory because of the relatively simple, standard-frame type construction for which assumptions were made.

C. Technical Operations Research Experiments

The "pumped source" method of simulating fallout by pumping a Co^{60} source through flexible plastic tubing positioned on the desired contamination area was developed by Tech Ops (Technical Operations Research). This simulation technique removes the necessity for actual fallout radiation in experiments designed to determine the radiation attenuation of structures. In initial experiments (Reference 21), tests were performed on six structures of varying characteristics. Included were an Army barracks type structure of heavy brick construction with a slate roof, a heavy reinforced concrete windowless structure with a half basement, an open hole, a reinforced concrete underground shelter, and two residential type structures--one wooden and one brick. The results of these experiments were compared with four different computational procedures. These were: (1) British AE Guide (Reference 9), (2) Tech Ops Procedure (Reference 22), (3) Office of Defense Mobilization (Reference 23), and (4) a preliminary issue of the AE Guide (Reference 24). All of the computational methods predicted protection factors which were conservative by a factor of 1.5 or greater when compared with experimental results. For the open hole and for the basements of the residential structures, the theoretical predictions were roughly a factor of 2 to 3 conservative except for very lightweight walls [< 5 pounds per square foot (psf)].

Tech Ops also has successfully used the pumped source method in other full-scale buildings. These include an office building (Reference 25), a simple structure with a basement (Reference 26), a concrete block house (Reference 27), and a British residence (Reference 28). In general, the experimental results were in good agreement with the Engineering Manual calculations for the roof and ground contributions.

Measurements reported in Reference 28 were made inside sand bag shelters erected in a "representative" British residence and in iron 1:12 scale models. (Since model experiments is the subject of the next section, no analysis of the model

part of the experiment is included here). Two points are worthy of note:

(1) the walls of the British house were 100 psf concrete block, which are heavier than "representative" U. S. residences, and

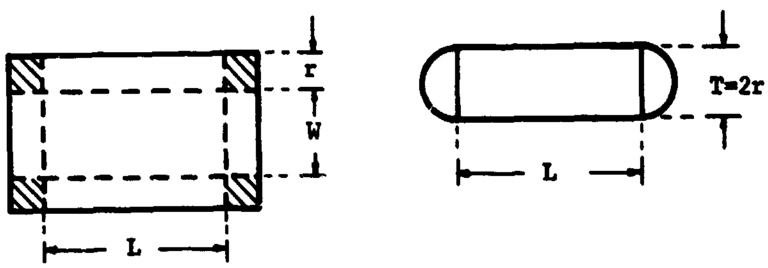
(2) the full-scale experimental results for a rectangular shelter with 125 psf walls compared with those for sand bags on stairs indicate that sand bags are less effective than anticipated.

Except for case (2) above, the Engineering Manual calculations agreed with the full-scale results.

In RTI's consideration of the problems found in shielding with sand bags, a sand bag was approximated by a rectangular solid with half round edges as shown in Figure 1.

FIGURE 1

Sand Bag Configuration



The volume of sand contained in a bag is given by

$$V = TLW + \left(\frac{T}{2}\right)^2 \pi\,(L + W) + \frac{2}{3}T^3 \qquad (1)$$

where $2/3\ T^3$ is the volume of the four corners shaded in Figure 1. If the sand bags are stacked like bricks (as was done in the British residence), the volume required by each sand bag is

$$V^* = (W + T)\ (l + T)\ T. \qquad (2)$$

If sand weighs 100 pounds per cubic foot and a sand bag is made with $L = 8$ inches, $W = 8$ inches, and $T = 4$ inches, then $V = 500$ cubic inches and $V^* = 576$ cubic inches. The bag would weigh 29 pounds and the void fraction would be

$$\frac{V^* - V}{V^*} = \frac{76}{576} = 0.133 \qquad (3)$$

or 13.3 percent. If the bag is made with $L = 8$ inches, $W = 4$ inches, and $T = 4$ inches, then $V = 318$ cubic inches and $V^* = 384$ cubic inches. The bag would weigh 18.4 pounds and the void portion would be 14 percent. Thus, for bags of reasonable weight, approximately one-seventh of the volume occupied by the barrier is actually void. Even neglecting radiation streaming through cracks, this represents a considerable reduction in shielding effectiveness. However, the British residence experiments indicate that radiation streaming through cracks is the real problem.

Perhaps a more efficient method of stacking sand bags could be found, or every seventh bag might be opened and the sand poured into the cracks. No reports of other sand bag studies are known to the authors. Further experiments and analyses on sand bag shielding are recommended.

C. Nuclear Defense Laboratory Experiments

The Nuclear Defense Laboratory (NDL) has conducted many experiments on simple full-scale structures. This work included determining attenuation of simulated (pumped source) fallout radiation by the roof of a concrete blockhouse (Reference 29), attenuation of fallout radiation (point sources) as a function of wall thickness in a concrete blockhouse (Reference 30), determination of lip contribution (ground penetrating radiation) in a foxhole (Reference 31), and dose rate measurements in various basement configurations (Reference 32).

In the work on contaminated roofs, Schmoke and Rexroad (Reference 29) found that experimental and theoretical reduction factors measured or computed along the vertical center line of the concrete blockhouse agreed quite closely (1-15 percent). The theoretical reduction factors were calculated using Spencer's Monograph (Reference 2). One interesting point was a shift in the relative position of the experimental and theoretical values with height above the floor. At the 6 foot height, the experimental values were slightly lower than the theoretical; at 3 feet the two practically coincide; and at floor level and 1 foot below the floor, the experimental values were higher than the theoretical. This behavior was believed to have been caused by the variation in backscattered radiation with height.

The corners of the blockhouse were found to offer considerably more protection from roof contamination than other locations in the structure. The experimental dose rates were from 40 to 70 percent higher at the center than at the corner for roof mass thicknesses of 3 to 50 psf at the 3 foot height.

Schmoke and Rexroad (Reference 30) later made measurements with Co^{60} and Cs^{137} ground level sources surrounding a concrete blockhouse with wall thicknesses ranging from 48 to 139 psf. These measurements were converted to reduction factors and compared with theoretical reduction factors computed using Spencer's Monograph (Reference 2). They found that the experimental and theoretical reduction factors agreed within $\pm$15 percent for the Co^{60} contaminated plane and within $\pm$20 percent of the Cs^{137} experiments. The exponential attenuation of dose rate as a function of wall thickness for all detector heights (0, 3, and 6 feet) was also confirmed.

In the lip contribution studies (Reference 31), Schumchyk and Tiller found that the dose rate contribution from the lip of a 4 foot diameter and 4 foot deep foxhole in an infinite contaminated field for depths of 1, 2, 3, and 4 feet on the vertical axis averaged 68 percent of the total dose rate in the foxhole for the case where lip contribution was measured and skyshine calculated, and 64 percent where both were calculated. Clearing an annulus 2 feet wide around the foxhole removed approximately 99 percent of the lip contribution.

In the basement experiments (Reference 32), various configurations have been tested. These included an open basement on which experiments have been completed, a basement with a flush floor slab, an open basement with a 2 foot high exposed wall, a basement with a 2 foot high exposed wall with various thicknesses of covers (at the 2 foot height) and various thicknesses of the 2 foot high wall. In the earlier experiments; i.e., open basement and with flush floor slab, deviation from Spencer (Reference 2) was found to be a maximum of 30 percent. As a rule, the theoretical predictions in basements were found to be non-conservative.

D. Defence Research Chemical Laboratories (DRCL) Experiments

DRCL (Reference 33) measured the dose distributions produced in a 15'x15'x8' sand-wood structure with movable partitions. The structure was exposed to 0.66 Mev gamma radiation from a Cs^{137} point source; and these results were compared with corresponding distributions in a 1:10 scaled iron model. The walls were constructed of sand between plywood to a total mass thickness of 27.7 psf, which is equivalent to 1.05 mean free paths for 0.66 Mev gammas. The roof mass thickness was 60 psf in order to make skyshine contributions negligible in comparison with wall contribution. This structure provided a protection factor of approximately 4 for an infinite uniform plane of contamination.

A point source of Cs^{137} was placed along the normal to the center of one exterior wall (front wall) at various distances from each of the two structures. Measurements were made with the source at two heights--on the ground and 40 inches above the ground. The source had a source strength of 30.6 r/hr at 1 meter.

DRCL found an increased dose rate of from 10 to 30 percent for detectors located mid-way between the center of their structure and the sidewalls when compared with detectors at the center. This increase was believed to be due to scattered radiation. They noted that the magnitude of the total dose scattered increases as the angle between the incident radiation and the surface normal is increased. Figure 9 of the DRCL report indicates that radiation incident at 60° to the normal to the sidewall scatters quite strongly

in a forward direction--approximately 80° to the normal. Thus, it appears that if the increase in dose contribution for the quarter axis detectors as compared with the center axis detectors were due to the scatter from the wooden sheathing of the structure, the increased dose would be in a location different from the front edge of the structure.

All of the results presented were for a point source of radiation. The effect of point sources rather than planes of contamination might account for part of the increase in dose rate at the quarter axis. Therefore, additional experiments of the type reported by DRCL for sidewall scattering should be performed with plane sources instead of point sources to determine the effect on quarter axis readings.

III. MODEL EXPERIMENTS

A. General

The modeling approach to measurements of radiation attenuation in structures was introduced in 1958 by Tech Ops when 1:12 scaled steel models of structures were used in tests for fallout protection.

In order to properly evaluate experimental work performed on building models, it is necessary to know the inherent uncertainties involved in scaling, the best method of alleviating these uncertainties, and the proper method of applying these results to full-scale structures.

The object of Tech Ops' first experiments (Reference 21) was further verification of the modeling technique as an economical means of obtaining shielding data on full-scale structures. The simulated structures were a concrete ranch house and a two-story wood frame house for which full-scale data were available in reports by Auxier, Buchanan, Eisenhauer, and Menker (Reference 34), and Batter, Kaplan, and Clarke (Reference 25), respectively. Perfect scaling was not possible because scaling laws call for increasing densities of all materials (air, ground, walls) by the same factor that reduces linear dimensions. Nevertheless, the feasibility and verification of the modeling technique for above-ground detector locations were demonstrated in these experiments. This initial work is also described by Batter and Clarke is the US NRDL Shielding Symposium Proceedings (Reference 35).

The object of subsequent experiments at the modeling facility was confirmation of protection factor computations for simple structures based on the methods developed for the OCD fallout shelter survey. Batter, Starbird, and York (Reference 36) and Batter and Starbird (Reference 37) investigated the effect of limited planes of contamination on the dose rate in a multistory windowless building. Starbird, Velletri, MacNeil, and Batter (Reference 38) and Velletri (Reference 39) studied the effect of interior partitions in the same structure. Batter and Velletri (Reference 40) measured the radiation reflected from ceilings. The major conclusions and recommendations reported by Tech Ops and the effect of these findings on PF computations are discussed in Reference 1 .

Detailed discussions of the results of the experiments on the multistory building are presented in Appendixes L, M, and N, of Reference 1. A comparison by RTI of the ratio of observed to calculated protection factors for the model (with its actual dimensions) with the same ratio for the full-size structure showed that essentially no error was introduced by the scaling process for above ground detector locations. It was recommended in Reference 1, however, that penetration data such as that presented in the charts in the Engineering Manual be developed for the radiation of Co^{60} and attenuation characteristics of steel.

Starbird and Batter (Reference 41) measured the angular distribution of skyshine radiation. Velletri, York, and Batter (Reference 28) determined protection factors of emergency shelters in models of British residences and compared these with the full-scale experiments which were discussed in an earlier section. Jones and Batter (Reference 42) reported a series of experiments using steel cylinders as the shield configuration to experimentally evaluate the function $G_s(\omega)$ for wall-scattered radiation. This function is one of the most uncertain parameters in the Engineering Manual Method, being admittedly based on assumptions. It is thus rather gratifying when calculated and experimental doses agree within 20 percent for an experiment designed to minimize other effects. The experiments do indicate apparent systematic differences between actual and assumed forms of $G_s(\omega)$. This report (Reference 42) recommends additional experiments to determine this function. However, because of the difficulty of isolating effects experimentally and the lack of theoretical work on this parameter, it is recommended that Monte Carlo calculations be performed to better understand the angular distributions of wall-scattered radiation. Meanwhile, the form currently in use seems to yield relatively accurate estimates of wall-scattered radiation.

B. Basement Dose Rates

One of the more important locations for shelter is in the basements of buildings. The Engineering Manual predictions of dose rates from contaminated flat roofs agree satisfactorily with full-scale experiments (See Chapter 3, Section II). Ground contamination will make a significant contribution to basement dose rates in tall buildings, or buildings with thick upper floors or roofs. NDL is currently conducting a series of full-scale experiments to investigate basement dose

rates arising from radioactive sources located on the ground outside the structure. As yet, no NDL data are available for a basement with both the first story walls and first floor in place. Engineering Manual predictions for the ground contribution can be compared, however, with model data reported by Tech Ops (Reference 43).

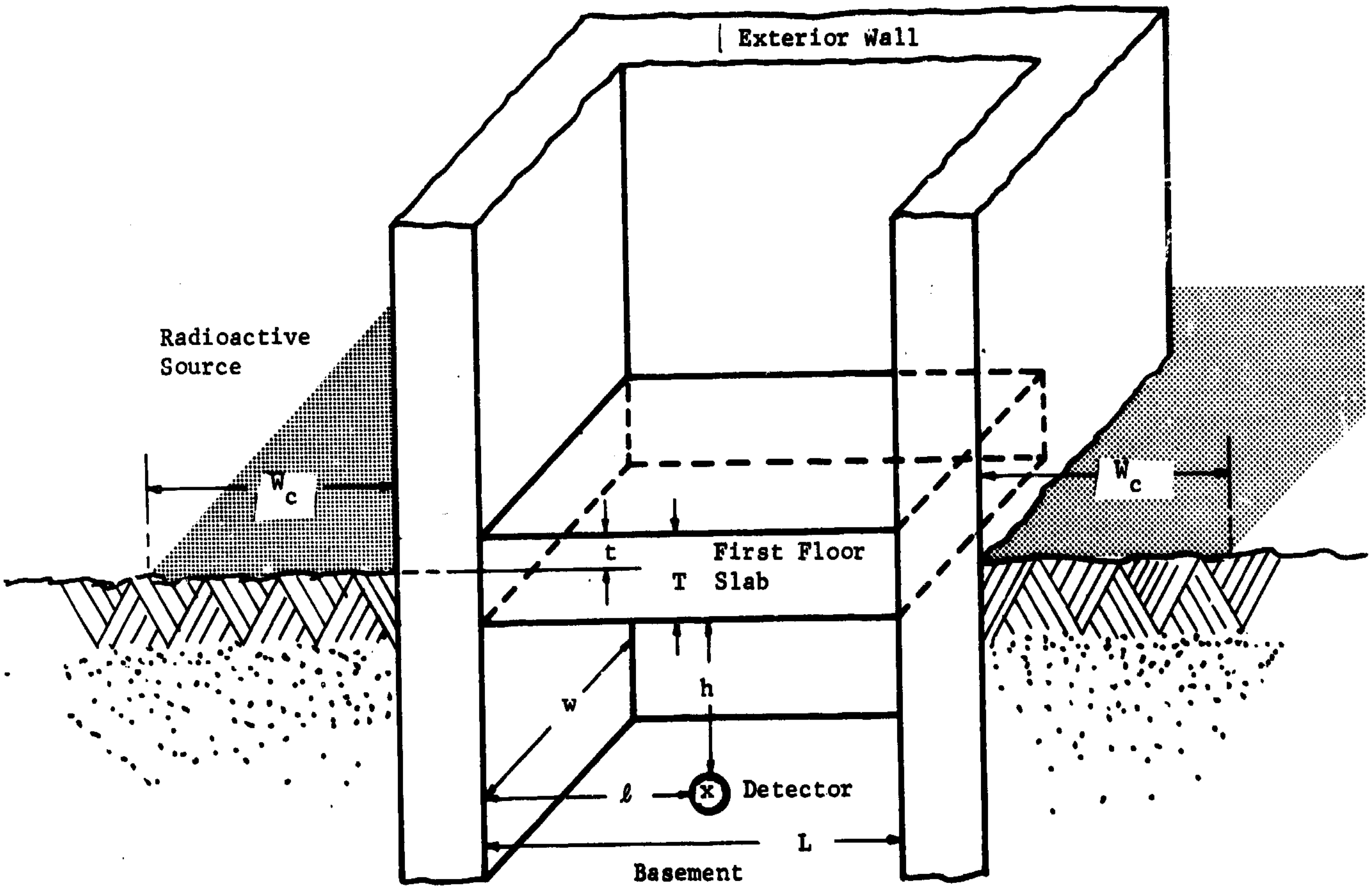
The Tech Ops' experiments were conducted with a 1:12 steel model representing a 72 foot high, six-story, 36 foot x 48 foot building with a full basement and 40 psf walls and 50 psf floors. Uniform ground contamination was simulated with Co^{60} point sources near the walls, and by the pumped source method at greater distances. In addition to dose rate measurements at three levels above each of the upper story floors at both center and corner locations, measurements were taken at various locations in the basement, with and without exposure of the first floor slab.

The detector locations for the basement measurements are shown in Figure 2. The dose rate may be expressed functionally in terms of the dimensions appearing in Figure 2 as $D\ (t/T,\ h,\ \ell/L,\ w/W,\ W_c)$. In Tech Ops' experiments, the first floor slab thickness T, and the plan dimensions W x L were held constant. Measurements of the dose rate were made with the upper surface of the first floor slab flush with the outside grade level ($t = 0$), with the first floor slab halfway exposed ($t/T = 0.5$), and with it fully exposed ($t/T = 1$). In other experiments, the detector was placed at different depths h, and at center ($\ell/L = w/W = 0.5$) and corner locations. Measurements were taken for rectangular strips of contamination with various widths W_c surrounding the building.

The basement data were scaled up by Tech Ops to full-scale structures. The scaling procedure was the same as that previously shown to be valid for upper story detector locations. Tech Ops noted that there is some difficulty in applying this procedure to basement dose rates. In their words, "There is some ambiguity in the choice of the proper first story height in making the correction (scale correction of the atmosphere). Radiation reaching a detector located in a basement by scattering from the above-ground structure predominately traverses paths from the location of contamination to the outer wall and to the ceiling of the first floor of the structure and then scatters to the basement. Thus it is appropriate to apply the model to full-scale correction factors computed for the mid-height of the first floor for all basement results." Because the scaling procedure for basements has not been proven valid by comparison with full-scale measurements, the question of

FIGURE 2

Cutaway Section of Building with First Floor Slab Partially Exposed



the validity of the scaled-up data of Tech Ops is open. It is recommended that suitable full-scale basement measurements be made to allow an evaluation of the scaling method for model data. In the sections below, the implications of Tech Ops basement data are discussed. It is recognized that errors of the type mentioned above may be present; nevertheless, it is felt that, although the absolute values may be different in a full-scale experiment, the trends displayed by the model data will also be present in a full-scale experiment.

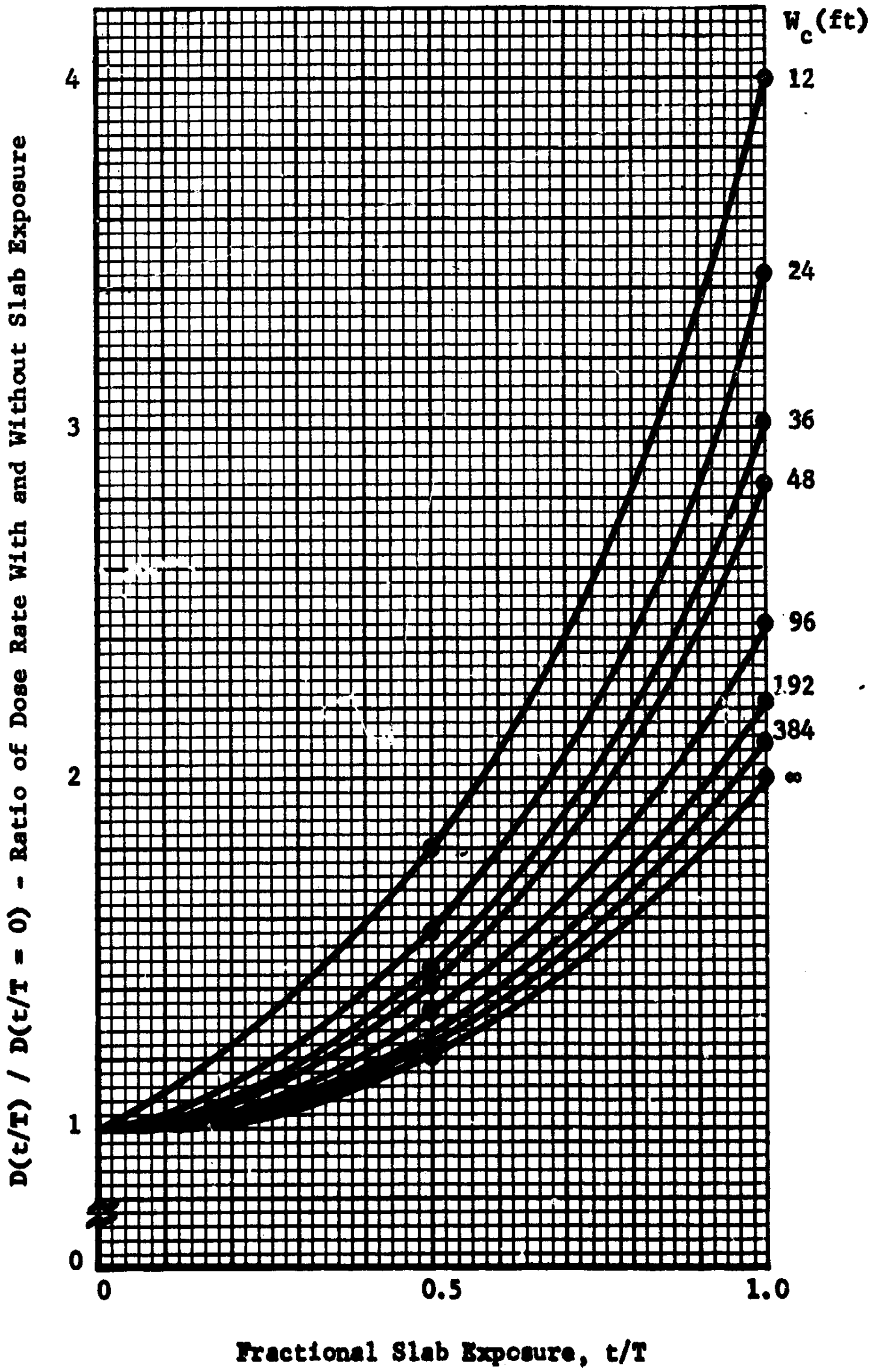
1. Effect of First Floor Slab Exposure for Various Limited Strips of Contamination

In PF calculations, it is assumed that either the upper surface of the first floor slab is flush with the outside grade level, or the basement wall is sufficiently exposed so that the radiation penetrating the wall below the slab is calculable. No method is available for treating the case in which the grade level lies between the upper and lower surfaces of the first floor slab. The magnitude of the increase in the basement dose rate due to fallout on the ground depends on the amount of slab exposure t/T and the width of the contaminated plane W_c. Tech Ops' data were used in Reference 44 to develop this dependence for a windowless structure with 40 psf walls and a 50 psf floor. In this sequence of measurements, the detector was located at h = 6 ft. below the center of the first floor slab, $\ell/L = w/W = 0.5$. The scaled-up results are summarized graphically in Figure 3 in which the dose rate with fractional slab exposure t/T relative to that without exposure, t/T = 0, is plotted versus slab exposure t/T for various contaminated plane widths W_c. It is seen that the basement dose rate increases by a factor of 2 for an infinite plane of contamination as the first floor slab becomes fully exposed, whereas the increase is by a factor of 4 for a 12-foot-wide plane adjacent to the building.

In order to evaluate this experiment, it is necessary to examine the modeling involved. The slab thicknesses in the model are adjusted to give the same mass thickness as is found in the full size structure. The models were built of steel; the full size structures are constructed of concrete. The density of steel is about three times that of concrete, but the model

FIGURE 3

Ratio of Basement Dose Rate 6 Feet Below First Floor Slab with Slab Exposure to That Without Slab Exposure for Various Contaminated Plane Widths for a Building with 40 psf Walls and 50 psf Floors



was built on a 1 to 12 scale. Therefore, to obtain the proper mass thickness, the slabs of steel should have been four times the thickness called for by the modeling scale.

The radiation received at a detector after scattering in a slab exposed on its edge is a function of the solid angle subtended by the slab edge at the scattering point, the scattering ability of the material, and the solid angle subtended by the slab at the detector. At a scattering point, the edge of the model slab subtends a solid angle approximately four times that subtended at the corresponding point by the slab edge of the full size structure. Also, the mass thickness per unit length of the slab is about three times greater in iron than in concrete. Thus, a unit volume in the model will scatter more than a unit volume in the structure.

The result of these effects will be to increase the dose seen by a detector in the model over those seen in a full-scale structure. Since the modeling is not accurate, the proper interpretation of the results is open to question. However, there probably will be an increase in the dose rate observed in the basement of a full size structure with an exposed first floor slab. It is therefore recommended that full-scale measurements be made of the effect of floor-edge scattering of radiation originating from grade level and entering a basement with a partially exposed first floor slab $0 \leq t/T \leq 1$. Although Tech Ops reported no measurements at a first story detector location with an exposed slab, it is expected that some increase will also occur there.

If the above recommended full-scale experiment verifies the model result that floor-edge scattering is important, it is recommended that a calculational procedure be developed for analyzing buildings with fractional first floor slab exposure. This effect is now neglected by the Engineering Manual and other procedures.

2. <u>Variation of Basement Dose Rate with Depth for Ground Contamination</u>

Tech Ops' scaled-up data for an infinite field ($W_c = \infty$) with a centrally located detector ($\ell/L = w/W = 0.5$) and an unexposed first floor slab ($t/T = 0$) show a slight initial increase, then decrease, in dose rate as the detector is moved downward (increasing h) in the basement. Engineering Manual calculations performed by Tech Ops are in approximate agreement with experimental data taken at 6 ft. below ground level, but

overestimate and underestimate the experimental dose rates at higher and lower detector positions, respectively. This variance is probably due to competing changes in inverse square spreading and slant attenuation by the floor slab. The change in angle of penetration through the floor slab (slant attenuation) of radiation scattered from the wall to a basement detector, as the detector is lowered, is not taken into account by the Engineering Manual. The directional response function in the Engineering Manual accounts for the inverse square spreading; however, the same floor barrier factor is used for all depths.

Reference 1 shows how these competitive changes in the direct or uncollided component of the radiation penetrating the floor slab can actually give rise to an initial increase in dose rate, then a decrease, as the detector is moved downward from the slab. The absence of an initial increase does not, however, imply the absence of these competing effects--it may mean only that the change in slant penetration never becomes dominant over the change in the inverse-distance-squared effect. On the other hand, a changing ratio of experimental to theoretical Engineering Manual dose rates with depth is strong evidence that the change in slant penetration is significant and should be incorporated into the floor barrier or geometry factors.

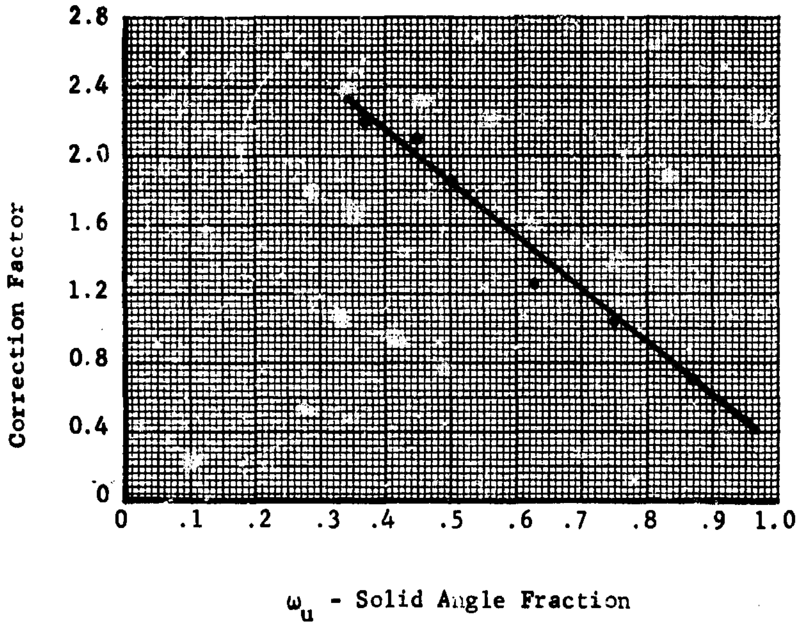
An empirical correction factor for the floor barrier factor was developed in Reference 1 from scaled-up data in the Tech Ops' report (Reference 43). The correction factor $C(\omega)$ is defined as the ratio of the experimental to the theoretical dose rate. It is seen in Figure 4 to be linear with the fractional solid angle subtended by the first floor slab as measured from the detector point. (This correction factor was calculated for ground radiation and does not apply to attenuation of roof radiation by the floor.)

$$C(\omega) = D_{exp}(\omega) \quad D_{theo}(\omega) = a + b\omega \qquad (4)$$

For the structure used by Tech Ops, a and b take on the values 3.5 and -1/3, respectively. In a more general situation, it is not unreasonable to expect that additional terms in the power series for $C(\omega)$ will be required, with coefficients dependent on the floor mass thickness. It is anticipated because of radiation coming from the walls, that a similar correction factor will be needed in the calculation of the contribution

FIGURE 4

Correction Factor for First Floor Slab Barrier Factor for Building Having a 50 psf Concrete First Story Floor and 40 psf Walls



through all upper floors.

Reference to Figure 4 shows that the correction factor for the Tech Ops' experiment varies from 0.65 to 2.2--a change of more than a factor of 3--as the detector depth varies from 3 feet to 18 feet. Even though Tech Ops' data do not indicate a very strong turnover in the dose rate with depth (i.e., initial increase then decrease), it is clear from the size of the correction factor required that the floor barrier needs re-examination. Because of the possible scaling errors in the Tech Ops' basement data, it is recommended that full-scale experiments be conducted with the objective of checking the accuracy of the floor barrier factor for radiation scattered from the first story walls into the basement.

3. <u>Variation of Basement Dose Rate in Horizontal Plane for Various Limited Strips of Contamination</u>

In the basement at h = 3 ft. below an unexposed (t/T = 0) first floor slab, the ratio of the dose rate at the corner location (ℓ=w=6 ft.) to that at the center (ℓ/L = w/W = 0.5) is essentially unity for an infinite field ($W_c = \infty$) and increases to 0.00052 / 0.00041 = 1.3 for a 24-foot wide plane (see Tech Ops' Figure 22). These results are in disagreement with the Engineering Manual which predicts that: (a) the basement corner location dose rate from ground sources is <u>lower</u> than that at the center, and (b) the variation of the basement dose rate in the horizontal plane is independent of the width W_c of the plane of contamination. (If the predominant contribution is from the roof, one would expect the dose rate to be greater in the center of the basement.) Although one may consider a 30 percent variation in dose rate to be of less importance than the larger factors encountered in the two previous sections, the variation is in such a direction to refute the wide spread belief, and frequently quoted view, that the safest place in a basement is always near the walls rather than in the center.

Because of the possible errors existing in the scaling procedure for basement data, the above discrepancy is not great enough to recommend a revision of the Engineering Manual at this time. Nevertheless, since the observation casts some doubt on a popular viewpoint, it is recommended that off-center measurements be made simultaneously with the other full-scale experiments recommended above. If the full-scale data obtained in these experiments confirm the scaled-up model data for the corner location, two revisions to the Engineering Manual will probably be required: (a) the floor barrier factor must account for the fact that the radiation penetrating the walls to the detector does so at a slant angle rather than penetrating about the normal as in the case of radiation from the roof and (b) the angular distribution of the radiation emerging from the interior surface of the walls, which is used to calculate the directional response G_s, must incorporate a dependence on the contaminated plane width.

Tech Ops also reported off-center measurements at greater depths in the basement. For a 15-foot-depth, the ratio of corner to center dose rate is 0.0012 / 0.0017 = 0.7 for an infinite field, and 0.0003 / 0.0004 = 0.7

(the same) for a 24-foot-wide plane. Although absolute agreement between experimental results and the Engineering Manual is shown by Tech Ops to be poor at the 15-foot-depth (Table 33, Reference 43), a less-than-unity ratio of corner to center experimental dose rate, independent of plane width, is the result expected from the Engineering Manual.

C. Interior Partitions

The effects of interior partitions on dose rates in a shelter have been studied by Tech Ops, NRDL and DRCL. The results indicate a considerable effect if there are many thin partitions or if there are a few of large mass thickness.

Tech Ops performed an experiment (Reference 45) with an iron model and a monodirectional source. The data show that two shield slabs are generally more effective than a single slab of equal mass thickness. Monte Carlo and Moments Method shielding calculations both agree with these experimental measurements. No comparisons were made with Engineering Manual methods, but this observed effect is in qualitative agreement with the Engineering Manual procedure of using the product of barrier factors, that is

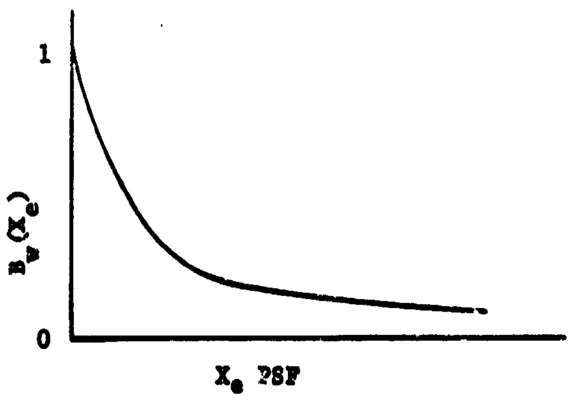
$$B_w = B_w(X_e)\, B_w(X_i). \qquad (5)$$

Figure 5 shows that for given X_e and X_i

$$B_w(X_e)\, B_w(X_i) \leq B_w(X_e + X_i) \qquad (6)$$

FIGURE 5

Interior Partition Barrier Factor Function



If a single barrier of the total mass of the parallel partitions is used in an analysis of compartmented structures, it should be regarded as a conservative method of calculating ground contribution.

In a study of buildup factors [1/] in a compartmented structure, NRDL (Reference 46) compared buildup factors in a model-sized compartmented structure simulating an aircraft carrier with single slab dose buildup factors. In these experiments, it was found that the buildup factor for the compartmented structure was, in every case, significantly lower than the single slab data. The greatest difference in the buildup factor was 30 percent and was for the deepest or most highly compartmented positions. The most important factors that contributed to the dose distributions were found to be slant penetration of gamma rays through material and the location of the source with respect to the shielding and detectors. The single slab data of Lynn and Scofield for plane-parallel radiation were found to always be higher than for the compartmented structure buildup factors.

In the experiments comparing models with full-scale structures, DRCL (Reference 33) found that 1:10 scaled model dose rates predicted full scale results reasonably accurately if there were no interior partitions. All partitions in the DRCL experiments were located perpendicular to the line of sight from the source to the detector. Even though these partitions were moved in the structures along this axis, the results were similar for a constant number of partitions. Measurements were made under exposure conditions designed to distinguish between the separate effects of dimensional scaling and environmental (ground and air density) scaling. DRCL's major conclusions were: (1) failure to scale the densities of ground and air will affect a 1:10 scale model shielding study by less than 10 percent and (2) iron is a suitable material for scaling simple concrete structures with uniform walls. An accuracy of $\pm$ 10 percent, depending on wall thickness, should be possible. For complex structures (i.e., highly compartmented) where most of radiation is channeled or multiply reflected before reaching a detector, iron models will overestimate building protection factor by greater than 10 percent.

[1/] The buildup factor represents the net increase in dose due to scattering.

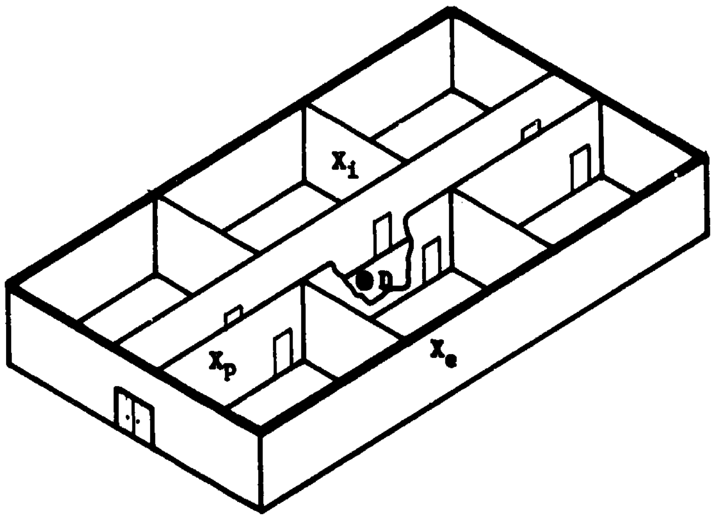
In an earlier report on compartmented structures, Engineering Manual calculations are nonconservative by 33 percent when compared to the experimental results (Reference 38). Reference 11 rather carefully analyzes these experiments and compares them with Engineering Manual calculations. The one refinement which can be recommended is that for interior partitions of the form shown in Figure 6,

$$B_w = B_w(X_e)\ B_w(X_p + kX_i) \tag{7}$$

with $k = \frac{1}{2}$ instead of the approximation of $k = 1$ originally used in Reference 11.

FIGURE 6

Parallel and Cross Partitions



D. Above - Ground Dose Rates

1. Infinite Plane of Contamination

After scaling up model data to full scale, Tech Ops (References 36 and 43) found excellent agreement (within 10 percent) of experimental and Engineering Manual computed infinite-field dose rates at the 3-foot first-story level for a centrally located detector. Agreement at the 3-foot central location for upper floors was good (within 20 percent). In these measurements, the full scale equivalent floor and wall mass thicknesses varied from 20 to 80 psf. The agreement of Engineering Manual calculations and model data gives support to the claim that the scaling procedure for simple structures with above-ground detectors is reasonable accurate.

2. Limited Planes of Contamination

a. Dose Rate Variation with W_c/H

Tech Ops also found that the dose rate data as a function of W_c/H (the ratio of the width W_c of the plane to the detector height above the plane H) for all six stories at a given detector height above the floor, and for a given floor mass thickness, in general followed a common curve for values of W_c/H less than 10 for both the corner and center cases. The first-story dose rates were, however, somewhat higher than the upper story values for the same W_c/H ratio for 80 psf floors. This difference was slight for 50 psf floors, and was due to the shadowing effect of the floor below a given detector.

Tech Ops compared the finite-field experimental data with the NationalFallout Shelter Survey Computer Program. The quantity compared was the multiplicative factor needed to correct the infinite-field ground contribution to the finite field case. Agreement was not good, from 3 to 100 percent, for $W_c/H < 10$ (see Table 25 of Reference 43), but there was general agreement for $W_c/H > 10$ (roughly within 30 percent).

b. Behavior of Far-Field Contribution

It was noted in Reference 44 that a simple and useful analytical fit could be obtained for the dose rate contribution measured by Tech Ops for various widths of strips of contamination. Consider the

scaled-up experimental values for the dose rates at various points in a full-size building resulting from limited strips of contamination with width to detector height ratios in the range $10 \leq W_c/H \leq 100$. These dose rates are expressed in Table 29 of Reference 43 as fractions of the infinite-field first-story dose rate. A plot of these data for a detector located at 3 feet above the center of the first floor defines a remarkably straight line on semilogarithmic graph paper of the form

$$M_L = a + b \ln (W_c/H) \tag{8}$$

in which M_L is the relative dose rate, and a and b are constants.

The utility of an analytic expression for far-field contributions can be illustrated with the following problem:

> Compute the dose rate relative to the infinite-field dose rate for a plane of contamination occupying the region $150 \leq W_c \leq 300$ ft. (i.e., the inner edge of the plane is 150 ft. away from the wall and its outer edge is 300 ft. away) if the relative dose rate 3 feet above the center of the first floor due to a plane width $30 \leq W_c \leq 150$ is 0.33 (data taken from Tech Ops Table 29). From equation (8), one can obtain
>
> $$\frac{M_{L2} - M_{L1}}{M_{L4} - M_{L3}} = \frac{\ln W_{c2} / W_{c1}}{\ln W_{c4} / W_{c3}} \tag{9}$$
>
> in which M_{L1} is the relative dose rate due to a rectangular strip extending a distance W_{c1} out from the wall. Substitute values and obtain
>
> $$M_{L2} - M_{L1} = 0.33 \frac{\ln 300/150}{\ln 150/30} = 0.14 \tag{10}$$
>
> This prediction compares favorably with Tech Ops experimentally observed value of 0.15.

In Reference 44 it is shown that equation (8) can be derived theoretically from the assumption that the dose rate per unit area of source distributed uniformally along a line parallel to the building walls and out a distance W_c from the walls varies inversely as the square of the geometric mean of the source-wall distance and the arithmetic mean source-detector distance, $W_c + \frac{1}{2} \left(\frac{W}{2} + \frac{L}{2} \right)$.

The basement data for limited strips also follow a straight line given by equation (8) within a few percent over the range $4 \leq W_c/H \leq 100$. Consequently, predictions such as that presented above are applicable to basement detectors as well.

3. Off-Center Detector Location

Tech Ops made dose rate measurements in corner locations 6 inches, corresponding to 6 feet in the full-scale building, in from the walls ($\ell = w = 6$ in.). These data show that the dose rate at an upper story corner position relative to that at the center depends significantly on the width of the plane of contamination and the floor mass thickness. Tech Ops (Table 28, Reference 43) asserts that for limited planes with $W_c/H \leq 10$, the corner dose rate 3 feet above the floor is 1.4 times the center dose rate for 20 psf floors, whereas it is 2.5 times for 80 psf floors. The corresponding factor for an infinite field and 50 psf floors is 1.04. In these experiments the narrowest plane studied was one that reached from the building out to 12 feet (full-scale). No comparisons were made for off-center dose rates with Engineering Manual predictions. It is recommended that Engineering Manual calculations be performed to allow such comparisons.

E. Ceiling Shine

Tech Ops has proposed a method for calculating ceiling shine (Reference 40). In most shelters for which a large contribution arises from the roof, direct, or wall-scattered radiation, the present Engineering Manual method of including an estimate of ceiling shine in the directional response for skyshine, $G_a(\omega)$, is probably adequate, since the total ceiling shine contribution is only on the order of 10 percent of the total dose. On an intermediate floor in a tall building, surrounded by tall buildings, with a large fraction of apertures and thick floors, the detector will see no direct radiation or skyshine, and little wall scatter from the adjacent walls and hardly any radiation from the roof or from the upper and lower floors. In this case the largest contribution will be due to radiation from the finite plane entering the apertures and reflecting from the ceiling. It is therefore recommended that the ceiling shine procedure be included in the revision of the Engineering Manual as an ancillary method for handling this class of configurations. When this procedure is employed, the ceiling shine correction in $G_a(\omega)$ must be removed, if skyshine is computed.

F. Non-Uniform Source Distribution

In Reference 44, Tech Ops data from Reference 43 for a model of a multistory windowless structure with 40 psf walls and 50 psf floors were used to determine the change in dose rate due to movement of fallout from one location to another, such as from the crown (center) of a street to its edge, or from the roof of the building to the sidewalk. For example, if a tall building (W = 36 ft., L = 48 ft. full-scale) were surrounded solely by a limited plane of width W_c = 24 feet, the relative increase in dose rate at a first story detector location would be 38 percent if all of the radioactivity on the roof fell on the ground next to the wall. If, however, the building had been surrounded by an infinite plane of contamination, the increase would have been only 8 percent. Therefore, redistribution of fallout does not cause a significant change in PF if there is an infinite plane of contamination.

IV. SIMULATED FALLOUT

A. Introduction

Tech Ops (Reference 21) developed the "pumped source" method of simulating fallout by pumping a Co^{60} source through flexible plastic tubing positioned on the desired contamination area.

A majority of the more recent shielding experiments (References 15, 18, 26, 27, 36, 38, 40 and 47) have employed the "pumped source" technique simulating fallout radiation. In order to determine the reliability of these experimental measurements, structures in which radiation measurements were made under actual fallout conditions were compared with measurements using the simulation method.

B. EG&G Experiments

During Operation Plumbbob Shot Shasta and Shot Diablo, a series of measurements were made by the Atomic Energy Commission in an above-ground building and an underground group shelter exposed to actual fallout conditions at the Nevada Test Site (NTS).

In order to compare pumped source results with actual fallout results, EG&G measured radiation levels at the same two structures at NTS but with simulated fallout produced with the pumped source technique (Reference 20). These measurements were compared with the measurements taken during actual fallout conditions.

EG&G used the Co^{60} "pumped source" method for measurements in both structures. The source was pumped at constant speed through the prepositioned, uniformly spaced tubing over the area where the fallout field was to be simulated. The source spent a constant time per unit area and, by time integrating the radiation rate with isotropic detectors, a constant density fallout field was simulated.

The radiation dosage at points within the above grade shelter was measured using a simulated contaminated area of known strength outside the building. Dose integrating detectors were used which caused the total radiation dosage to appear to be from an area source. This technique averaged local features of the terrain and ground roughness in a manner similar to that done in the actual fallout field. The dose contribution from fallout on the roof of the building was determined by spacing the tubing on the roof. An 18.6 curie source was used for this case.

For the underground group shelter, the tubing was placed above and immediately surrounding the shelter. A 259-curie source was used for this case and the integrated dose was measured at various heights and positions within the shelter.

For the Shasta shot, dose rates and fallout deposition were measured inside and outside the building. Contributions to dose rate from the roof and ground were determined from these measurements.

Protection factors were also determined for the above ground shelter from data taken using the pumped source method. The pumped source protection factors, which varied from 2 to 50, were conservative and agreed within roughly a factor of 2 with those determined from fallout data. These results were in good agreement in view of the limitations of the data and various other parameters which would influence the differences in protection factors. These parameters were ground roughness effects, energy spectra, and nonuniformity of fallout. Although ground roughness was an important parameter in influencing the difference in protection factors between the pumped source results and the actual fallout results, the effect of ground roughness on the actual fallout results is not clear. The protection factor was determined at a 3-foot height by dividing the outside dose rate by the inside dose rate and assuming that the ground was perfectly smooth. Ground roughness affects both the inside and outside dose rates; however, the inside dose rate would be decreased more by ground roughness than the outside dose rate. This would result in a higher, or less conservative, protection factor. This is because of the more nearly horizontal travel of the gamma rays to an inside detector when compared with one on the outside. Changing the amount of roughness for this case would only modify the results slightly because the tests were performed on relatively smooth desert terrain and the tubing of the pumped source method also elevates the source above the roughness.

EG&G compared their results with Engineering Manual calculations and found that the calculations were conservative (lower than actual PF) for all cases except the basement with both roof and ground contributions. Considering experimental error may remove this non-conservatism for this case since the results were within approximately 4 percent and could easily reverse in subsequent measurements. The other trend shown is that the calculations were more conservative for the first story detector than for the basement detector. This seems reasonable since roof contribution is important in unexposed basements and is not affected by parameters such as ground roughness.

For all cases except the one in the basement with both ground and roof contributions, the pumped source method of simulating fallout compared within 15 to 40 percent of the actual fallout results. In every case, the pumped source method is conservative when compared with the actual fallout. Heavy precipitation occurred in the Shasta event prior to first complete measurements. This precipitation washed away much of the fallout on the roof; resulting in density of fallout on the roof equal to only 1/10 of that on the ground. The fact that the basement detector was drastically affected by precipitation, while a first story detector was not, agrees with theory.

Co^{60} pumped source measurements were compared with theoretical calculations. The theoretical and experimental results were found to agree within 20 percent at the 1-foot level but varied as much as a factor of 2 for a 6-foot level detector. Part of this difference was attributed to the wooden frames over the basement and errors in the assumed mass thickness of the corrugated steel walls.

Measurements of radiation intensity were made during shot Diablo at various positions inside the underground shelter from fallout deposited on ground outside. Measurements were made at the same locations as in shot Diablo with the pumped source method instead of real fallout.

The protection factors in the shelter itself were found to vary from 10,000 to 20,000 in the fallout situation (Reference 48). Similar results were obtained using the simulated fallout (Reference 20). Near the vents in the roof, the protection factors varied from 2,000 to 5,000 for both sets of measurements, which still gave considerable fallout protection.

Various factors were found to cause the results to vary between the EG&G pumped source experiments and the measurements in real fallout. These factors, which are applicable for both the above ground shelter and the underground shelter, are discussed below.

Some of the factors which might have influenced experimental data were variations in source calibrations; differences in energy response and angular response between high-and-low range ionization chambers; errors in recording time, temperature and pressure which would affect instrument electronics and corrections for air density; and errors in distance measurements.

Although it was thought that ground roughness and nonuniform fallout would affect the experiments, results showed that the pumped source technique was quite accurate in predicting real fallout.

C. NRDL

The Naval Radiological Defense Laboratory (NRDL) (Reference 46), also used the pumped source method in their studies of ship shielding. They found that this is a satisfactory method of simulating actual fallout radiation in compartmented structures.

D. Recommendations

The recommendations which resulted from the analysis of pumped source experiments are:

1. Although results in the experiments which compared the pumped source method with real fallout were quite similar, effects of ground roughness on pumped source results should be measured. For rough terrain such as plowed fields, macroscopic ground roughness would affect real fallout fields to a greater degree than it would the pumped source. Although microscopic roughness would not affect the pumped source, macroscopic roughness with larger clumps of earth would affect these results.

2. A Monte Carlo calculation to predict the effect of macroscopic roughness on the pumped source method of simulating fallout is recommended.

V. GROUND ROUGHNESS

A. Introduction

Present methods of computing protection factors of buildings subjected to fallout assume that the fallout is located on smooth planes. All earth surfaces are rough to some extent and the effect of this ground roughness on PF's should be determined.

Any irregularities of the ground surface will physically block the paths of gamma rays coming from contaminated planes. This results in a reduction in intensity in the gamma radiation since the gamma rays must penetrate a substantial amount of dense material before penetrating the structure.

B. NRDL

The most common method of correcting for ground roughness has been to assume that the fallout is buried under a layer of material. If this method is satisfactory, the dose angular distribution at a height H above a rough plane would be the same as the dose angular distribution at some height, $H + \tau$, above a smooth plane in which τ is the equivalent distance in air corresponding to the same amount of shielding.

Ferguson (Reference 49) derived a value of τ to account for ground roughness in four experiments over desert terrain. Values of τ ranged from 13 feet for angular distribution measurements to 37 feet for dose as a function of height measurements. Ferguson concluded that the angular distribution of direct radiation of various energies due to rough surfaces could be produced fairly well by putting in a layer of air-equivalent meterial. He also found that a difference existed between the calculated and predicted skyshine and felt that this problem needs further consideration.

C. EG&G

EG&G (Reference 50) investigated the effect of ground roughness on the radiation field above ground which had been contaminated with real fallout from a nuclear device. The two different types of Nevada terrain studied were: (1) a flat dry-lake bed, and (2) desert terrain. Experiments were also performed on a plowed field with a known degree of roughness,but questionable results

(attenuation of plowed field less than non-plowed field) necessitate rejection of these data. They found air-equivalent distances of 20 and 40 feet for the dry-lake bed and desert terrain, respectively. The air-equivalent distances obtained from the desert terrain experiment for both dose-angular distribution and dose as a function of height measurements were consistent. EG&G concluded that the method of describing ground roughness as if fallout were uniformly buried beneath a layer of earth is satisfactory.

D. DRCL

DRCL (Reference 51) measured the effects of ground roughness on the dose rate observed above a field contaminated with a single Cs^{137} point source at various locations. The effects of two types of roughened fields were studied. Both fields used concrete slabs arranged with a 45^{o} sawtooth profile of 6-inch trough to peak distance. A circular field in which the sawtooth profiles were concentric circles and were always at right angles to the direct path to the detector represented an extreme case of ground roughness. In a rectangular field, the sawtooth profiles were straight parallel lines and corresponded to a freshly plowed field. Various distributions of contamination were used in both cases, such as a uniform distribution on the peaks and in the hollows, as well as an extreme case where the contamination was only in the hollows. The difference was considered to correspond to various degrees of weathering of fallout.

For the circular field, the detector heights were varied from 1 to 19.3 meters and the distance from the detector to the source was varied out to 70 meters. For the rectangular field, the detector height was fixed at 1 meter.

DRCL concluded that ground roughness greatly reduces the dose received by a detector near ground level when compared with a smooth plane. This effect varied markedly with the large scale terrain features and with the height of the detector. Also, the location of the source (hollows or uniformly distributed) greatly influenced the results. Failure to allow for the effects of ground roughness could overestimate the dose rate measured at 3 feet above the ground by a factor of 2 for moderate roughness such as a plowed field, or as much as a factor of 7 for severe roughness such as the 6-inch concrete profile. These values were obtained from experimental data which showed that the ground roughness factor (factor by which a dose rate is multiplied to account for ground roughness) for the rectangular field varied from 0.45 (factor of 2) with uniformly distributed sources to 0.23 with sources located in the hollows. For the circular field,

corresponding values were 0.38 for uniform distribution and 0.13 (factor of 7) for sources located in the hollows.

E. Experimental Problem Areas

The major problems in all of these ground roughness experiments have been limitations on types of terrain studied, instrumentation difficulties, and translation of results into a form satisfactory for computation procedures. The method of determining the effects of ground roughness by a ground roughness factor or assuming an equivalent layer of air, τ, appears adequate.

Eisenhauer (Reference 52) proposed an experiment designed to measure the effects of microscopic ground roughness on dose rates. He reviewed existing calculational procedures for predicting these effects and then proposed an experiment to measure a correction factor to the angular distribution of radiation above a smooth plane. The main experimental conditions required included: good physical simulant of fallout particles (spectrum was listed as of secondary importance), size of contaminated area, source to detector distance large enough to minimize relative uncertainty in angular distribution (cos θ), and detector small enough to allow increment of cos θ of 0.01 in region $0 \leq \cos\theta \leq 0.2$.

F. Recommendations

The recommendations which resulted from an analysis of the ground roughness experiments are:

1. A factor of 2 should be used to decrease the dose rate above moderately rough terrain (plowed ground) to account for ground roughness.
2. Additional ground roughness experiments should be performed on surfaces most frequently occurring around fallout shelters. It is recommended that laboratory model tests be performed on geometrically simple ground roughness patterns like parallel furrows or circular patterns using scaled contamination and roughness. If these results indicate significant reductions in dose rates due to ground roughness, full-scale measurements should be made to determine ground roughness factors for surfaces expected around fallout shelters. Examples of such surfaces are grass, sidewalks, tar and gravel roofs, and city streets.

3. Better instrumentation should be used on all future ground roughness tests since one of the major problems on past experiments was caused by instrument errors and the influence of heat, dust, and low intensity measurements on instrument stability.

4. Although floor-edge scattering was found to be important if the first floor slab were exposed (above ground), experiments were performed on smooth surfaces and the effect of ground roughness was unknown. Therefore, measurements should be performed to determine the effect of ground roughness in a basement and first story with the first floor slab partially and fully exposed.

5. It is important to select a means for obtaining experimental information on ground roughness effects without nuclear fallout. Since it is incorrect to use the "pumped source" method of simulating fallout in these experiments because the continuous tubing eliminates much of the roughness effect, the only satisfactory method of simulating sources for these experiments is to use many point sources of radiation located on the ground surfaces. Allowances for difference in energy spectra between fallout and these point sources must be made but should be of secondary importance.

CHAPTER 3

Status of Theoretical Prediction of Experimental Results

I. INTRODUCTION

Many experimental and theoretical investigations of structure shielding against fallout radiation have been undertaken. Several procedures for computing the PF of shelter have been developed; the most accurate being the Engineering Manual, which is an analytical procedure based on the theory of Spencer's Monograph. Also, several computer programs have been developed to remove the lengthy hand calculations involved in the various procedures. The most recent and complete review and bibliography of shielding documentation is Spencer and Hubbell's NBS Monograph 69 (Reference 53) in which 485 references to unclassified literature are presented. A number of the calculations and supporting experiments are summarized in this monograph. Additional references may be found in an earlier RTI report (Reference 1) and in this report.

In this chapter, the various procedures for calculating PF's and several PF computer programs are summarized.

II. SPENCER'S MONOGRAPH

The basis for computation of protection afforded by materials and geometries is given in Spencer's Monograph 42 (Reference 2); however, the techniques presented are quite complex and not easily applicable to calculation of real structures. The predictions of dose rates from contaminated flat roofs were experimentally confirmed by Schmoke and Rexroad (Reference 29). Later experimental measurements with Co^{60} sources surrounding a concrete block house with wall thicknesses up to 140 psf agreed with theory to within $\pm$ 15 percent (Reference 30). The theoretical dose angular distributions above an infinite fallout field, from which other penetration data are computed, and the dose rate variation with height are in good agreement with measurements in actual fallout fields in Nevada (Reference 50). The observed absolute dose rates, however, were an unexplained 30-40 percent less than the calculated values.

III. ENGINEERING MANUAL

A. Introduction

The OCD Engineering Manual (EM) (Reference 4) method of computing PF's was developed to provide a systematic and practical approach to analyzing complicated, realistic structures without neglecting significant features of the building-source configuration. It's charts were derived from basic attenuation data in Spencer's Monograph and have been revised several times to incorporate additional information. The Engineering Manual is therefore the most accurate method of computing PF's and as such is the most widely used of the computational procedures. Many experiments, as described in Chapter 2, have been performed to determine the accuracy of the EM theoretical predictions. The subjects discussed below are areas that have been questioned or for which experimental data significantly disagree with the EM procedure.

B. Azimuthal Sectors

Azimuthal sectors are used in Engineering Manual computations (Reference 4) to handle irregularities in source and building configurations. For the majority of the buildings, the azimuthal sector method permits significant improvements over other PF computational methods. In the present method, an off-center azimuthal sector of a finite plane of contamination contributes the same amount of dose rate to a centrally located detector as does a centrally located sector of the same size. An error in this approximation can be determined from data of a Tech Ops model experiment (p. 28 of Reference 47) where dose rate measurements were made corresponding to 2.5 feet above the center of the first floor of a building with 80 psf walls. For two limited planes of contamination whose centers were located 12.5° and 33.7°, respectively, from the detector axis the ratio of observed dose rates was 1.93. On a per-unit angle of azimuthal sector basis this ratio was 1.65. For 80 psf walls, this shows that an azimuthal sector centered about the 12.5° angle will give a 65 percent larger dose rate than one centered about a 34° angle. For a larger range of angles and thicker walls, a wider variation in the dose rates will occur.

It has been shown (Reference 1) that most sources of contamination encountered in a statistically chosen sample of buildings were off-center finite

planes rather than infinite planes, or were finite planes extending the entire length of a wall. The variation in dose rate of off-center to center finite planes is due primarily to the slant penetration through the wall. In the present method an average slant penetration for an entire wall is assumed. Thus, for centrally located azimuthal sectors a non-conservative protection factor would result and for off-center sectors a conservative protection factor would be predicted. If contributions per degree from all sectors on a building side are about equal, the variation will average out so that no improvement for slant penetration can be made to the Engineering Manual. However, experience in analyzing actual structures has shown that this is not the case for most buildings.

Since all of the more accurate methods for computing PF's (including the various computer programs) use the azimuthal sector method, it is recommended that a more accurate procedure be incorporated into the present Engineering Manual procedure to account for the variation in contribution of azimuthal sectors of identical size centered on different azimuthal angles. Subsequent incorporation into computer programs is advisable.

C. First Floor Slab Exposure

The experimental basement dose rate increases by a factor of 2 for an infinite plane of contamination as the first floor slab becomes fully exposed, whereas the increase is a factor of 4 for a 12-foot-wide plane adjacent to the building. No calculational procedure is available for this effect. (Chapter 2, Section III.B.1. and Reference 43).

D. Variation of Basement Dose Rate with Depth

For a centrally located basement detector in a model structure, a slight initial increase, then decrease, in dose rate occurs as the detector is moved downward. Engineering Manual calculations are in approximate agreement with experimental data at 6 feet below ground level, but overestimate (50 percent) and underestimate (40 percent) the experimental dose rates at 3-foot deep and 12-foot deep detector positions, respectively. (Chapter 2, Section III.B.2. and Reference 43).

E. Variation of Basement Dose Rate in Horizontal Plane

The ratio of the model experimental dose rate at an unexposed basement

corner location to that at the center is essentially unity for an infinite field and increases to 1.3 for a 24-foot wide plane. These results are in disagreement with the Engineering Manual which predicts that: (a) the dose rate at a corner location in a basement from ground sources is lower than that at the center, and (b) the variation of the basement dose rate in the horizontal plane is independent of the width W_c of the plane of contamination. (Chapter 2, Section III.B.3. and Reference 43).

F. Interior Partitions

If a single barrier of the total parallel interior partitions is used in an analysis of compartmented structures, it should be regarded as a conservative method of calculating ground contribution. A more correct method of calculation is to add 50 percent of the average cross partition psf to that of the parallel partition psf. (Chapter 2, Section III.C. and References 11 and 45).

G. Ceiling Shine

In current OCD Fallout Shelter Analysis courses, AE's are taught to not shield skyshine. This will compensate for the effect of ceiling shine in buildings which have adjacent mutual shielding buildings since ceiling shine is only on the order of 10 percent of the total dose. However, in buildings with no mutual shielding, the method for calculating ceiling shine proposed by Tech Ops should be used. (Chapter 2, Section III.E. and Reference 40).

H. Ground Roughness

No factor for ground roughness is currently considered in the AE Fallout Shelter Analysis Courses. Nevertheless, a plowed field can reduce the total ground contribution by as much as a factor 2.

IV. RTI CDC-3600 PF COMPUTER PROGRAM

This Research Triangle Institute PF Computer Program (Reference 13) is based on the methods of the Engineering Manual, PM 100-1, (Reference 4). The program considers contributions from the roof, roof setbacks, and limited planes of contamination (including areaways). The effects of apertures, interior partitions, floors, detector height above planes of contamination, mutual shielding and building geometry are included. PF's in partial basements and basement extensions (such as under a sidewalk) can be calculated.

Input data are reported for the entire building and the protection factor is determined for each reported story. Building and contaminated plane dimensions are reported to the nearest foot; mass thicknesses are reported to the nearest pound. Three planes of contamination may be reported for up to three azimuthal sectors per building side, thereby giving considerable flexibility in the consideration of adjacent shielding buildings. Up to four interior partitions parallel to Side A and four parallel to Side B may be reported. The exact locations of these partitions are considered for roof contribution. Cross partitions are considered by adding 0.5 of their average psf to the nearest parallel partition. Aperture sill heights are reported to the nearest foot.

This program is capable of determining the PF in the center of the building part, at eight other pre-determined detector locations, and at one additional arbitrary detector location. The desired location of the additional detector must be indicated on the Data Collection Form. On the basis of the PF's at these points, the approximate area of the building part having a given protection factor is determined.

An edit program that checks for inconsistencies in the input data is included.

V. RTI UNIVAC 1105 COMPUTER PROGRAM FOR KEY FACILITIES

Key facilities, such as power plants, water plants, etc., are usually of non-uniform construction, irregular shape, and in some cases they have significant interior equipment. This computer program (Reference 54) is based on the Engineering Manual (Reference 4) and was developed to compute the PF's of key facilities. It is designed to be very flexible and permit the user to account for special building and contaminated plane details.

Contributions from setbacks below the detector and limited planes of contamination (including areaways) are calculated for the detector story and the stories above and below the detector story. The effects of apertures, interior partitions, mutual shielding, and building geometry are included. Roof contribution is not calculated and must be done by hand and added to the machine computed ground contribution.

Major differences between the program and other programs used in surveys of structures are:

(1) more azimuthal sectors (up to 20) are allowed and building construction changes (walls, partitions, and apertures) may be reported in each sector,

(2) major interior contents can be considered,

(3) major changes in vertical construction can be handled by using a zero floor weight at the point of change, and

(4) irregularly shaped structures can have a different shape factor input for each azimuthal sector.

All measurements are made for a specific detector location on the first story (the same relative location is computed on all other stories). Frequently, a specific detector location at an off-center location is needed to evaluate various operations in a fallout environment. Input data for each sector are reported almost independently of the other sectors with the only common data being floor and ceiling weights and heights of the detector story, story above, and story below. Dimensions are reported to the nearest foot and mass thicknesses to the nearest psf.

VI. PRAEGER-KAVANAGH-WATERBURY COMPUTER PROGRAM

The computer program "Electronic Analysis of Structures for Fallout Gamma Radiation Shielding" (Reference 12) was prepared by Praeger-Kavanagh-Waterbury (PKW), Engineers Architects, to calculate a PF for any detector location utilizing the methodology of the Engineering Manual (Reference 4).

In the PKW program, building dimensions are reported to the nearest foot (one W x L per building) and mass thicknesses within the structures are reported to the nearest 10 psf (pounds per square foot). Contaminated planes are reported for an entire building side and only one contaminated plane width is reported. Ten detector locations (one variable) may be calculated for one story. Input data are reported for a specific story and must be changed for detector locations on other stories. Aperture data are reported for the detector story and the adjacent stories above and below this story. The sill height is fixed at either 0 or 3 feet. Provision is made for up to four interior partitions parallel to Side A and four parallel to Side B of the building. The parallel partitions are combined and 0.4 of cross partitions psf is added for ground contribution. For roof contribution, an "average" location is used for the combined partitions. One wall weight is reported for each side of the building with no change on stories above and below the detector story. There is no provision for setbacks.

VII. EQUIVALENT BUILDING METHOD

A somewhat simplified method for computing PF's, called the "Equivalent Building Method" (Reference 6), has been advanced by LeDoux. This method is an approximation based on a reformulation of numerous calculations from the Engineering Manual. In essence, mass thicknesses are adjusted in AE Guide-type (Reference 3) charts to account for departures from simple geometries, thus providing an improvement in accuracy over the straight AE Guide method, yet not requiring the tedium of a full Engineering Manual calculation. In comparisons with the illustrative examples in the Engineering Manual, this method generally yielded results which agreed within 10 percent for buildings in the range of 100 to 100,000 square feet in area. However, using the procedure outside of this range of areas may result in differences of up to 30 percent for very large areas.

Whereas the Engineering Manual is very well suited for PF analysis, the LeDoux method offers advantages of speed and simplicity when comparison of alternative structure designs is involved. The latter method is more streamlined, yet has sufficient flexibility to determine the relative effectiveness of alternatives in design.

VIII. AE GUIDE AND NFSS COMPUTER PROGRAM

The AE Guide (Reference 3), another approximation to the Engineering Manual which offers a quick answer for simple structures, formed the basis for the National Fallout Shelter Survey Computer Program (NFSSCP) (Reference 7). In some cases the AE Guide is superior to the NFSSCP, while for other cases the Computer Program is superior. For example, the AE Guide is better for sill height corrections, but the Computer Program is better for limited planes of contamination. The advantages and shortcomings of these methods are discussed in Reference 1.

Tech Ops experiments showed that the NFSS Computer Program correction for near-field limited planes of contamination can lead to considerable error in the case of thick floors.

A recommendation for handling cross interior partitions in both the AE Guide and NFSSCP, based on Tech Ops experimental observations (References 38 and 39), was made in Reference 1. It was also recommended that additional experiments be conducted to investigate the effect of cross partition spacing on attenuation.

IX. CANADIAN AND BRITISH AE GUIDES

Reference 8 is the Canadian AE Guide,which contains the same charts as Reference 3. The British Home Office also has prepared a document (see Reference 9) for PF computations. British AE Guide predictions for a British house modeled by Tech Ops (Reference 28) were about 2 to 3 times those measured experimentally in the full-scale house and calculated using the Engineering Manual.

X. PROTECTION FACTOR ESTIMATOR

This document (Refernce 14) is a simplified version of the Equivalent Building Method (Reference 6). It contains curves for small and large buildings of 1,000 and 10,000 square feet in area, respectively. Between these limits, the accuracy for simple structures is within 10 percent of Engineering Manual calculations. Outside these limits, the difference may be as much as 35 percent. Buildings with extensive mutual shielding or basement exposure sometimes yield 20 percent differences even within the 1,000 to 10,000 area range.

XI. POINT - KERNEL METHOD

An approach (Reference 10) which has been used for calculating dose rates for some structures at the Nevada Test Site (Reference 34) is that in vogue for nuclear reactor shielding analysis. It consists of summing the doses from representative point sources using the build-up factor concept to account for multiple scattering. The computed intensities from ground sources were about 90 percent of the observed intensities for light shielding, and increased to 150 percent for heavier shielding. For roof sources, the percentage was 80 for light shielding and decreased for heavier shielding. These structures have also been analyzed by Eisenhauer (Reference 55). The point-kernel method in Reference 10 has the flexibility of locating sources anywhere, thus being able to simulate non-uniform source distributions, airborne fallout, and a variety of as yet uninvestigated problems. It was used to determine the effects of interior partitions on the ground contribution (Reference 56) and to study the influence of roof pitch on the roof contribution (Reference 57). The chief disadvantages are that it is highly specialized, requires considerable computer time, and hence is not readily adaptable to wide-spread use. Unlike reactor problems, the fallout source extends over large (possibly unbounded) areas which require excessive geometrical ray-tracing.

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Appendix A

Scope of Work - Contract OCD-PS-64-56

Evaluate information on shielding such as the effect of interior partitions, ground roughness, finite planes, apertures, ceiling shine, basement exposure, etc., for application to the computation of protection factors.

THE RESEARCH TRIANGLE INSTITUTE, Durham, North Carolina
OCD Work Unit 1115C - Final Report R-OU-155

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30 November 1965 (UNCLASSIFIED) 61 pp.

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ANALYSIS, GAMMA RAYS, SHIELDING, DATA, SCIENTIFIC RESEARCH, PROTECTION FACTOR, FALLOUT SHELTERS, UNDERGROUND STRUCTURES, STRUCTURES.

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